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MID-INFRARED OPTICALLY PUMPED, UNSTABLE RESONATOR LASERS (Preprint)

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14. ABSTRACT

The authors describe high-brightness, broad area midinfrared semiconductor lasers. These devices were fabricated in the authors' laboratory using a commercial solid-source molecular beam epitaxial system. The laser structures incorporated 14 type-II quantum wells embedded in thick waveguide/absorber regions composed of $In_{0.2}Ga_{0.8}As_{0.18}Sb_{0.82}$. The optically pumped devices achieved higher brightness operation as unstable resonators. Each unstable resonator was realized by polishing a diverging cylindrical mirror at one of the facets. For an unstable resonator semiconductor laser operating at ≈ 4.6 μm, near 84 K, and at a peak power of 6.7 W, the device was observed to be nearly diffraction limited at 25 times threshold. In comparison, a standard Fabry-Pérot laser was observed to be many times diffraction limited when operated under similar conditions

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Mid-infrared, optically pumped, unstable resonator lasers

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We describe high-brightness, broad-area mid-infrared (IR) semiconductor lasers. These devices were fabricated in our laboratory using a commercial solid-source molecular beam epitaxial (MBE) system. The laser structures incorporated fourteen type-II quantum wells embedded in thick waveguide/absorber regions composed of $In_{0.2}Ga_{0.8}As_{0.18}Sb_{0.82}$. The optically pumped devices achieved higher brightness operation as unstable resonators. Each unstable resonator was realized by polishing a diverging cylindrical mirror at one of the facets. For an unstable resonator semiconductor laser operating at ~ 4.6 μm, near 84 K, and at a peak power of 6.7 W, the device was observed to be nearly diffraction limited at 25 times threshold. In comparison, a standard Fabry-Perot laser was observed to be many times diffraction limited when operated under similar conditions.

High power optically pumped mid-IR lasers have been demonstrated with peak powers in the 5 to 15 W range, CW powers in excess of 2 W and lasing wavelengths in the 2 to 10 micron region.[1,2] However, these broad area lasers typically display degraded beam quality as the pump intensity is increased; they may go from 2-3 times diffraction-limited near threshold to 8-15 times diffraction-limited at ~ 30 times threshold. This limits the devices applicability since it becomes difficult to couple the radiation into a small aperture fiber or to focus the radiation in the far field. There are a large number of applications that would directly benefit from high power mid-IR output with a nearly diffraction limited beam. These applications include infrared countermeasures, free-space optical communication, remote sensing, laser marking, and various medical applications.

A number of approaches have been utilized in near-IR semiconductor diode lasers to achieve high-power operation with diffraction limited output. These include tapered amplifiers[3], angled injection into traveling wave or reflective wave amplifiers[4], coupled narrow stripe lasers, and various unstable resonator (UR) geometries[5,6]. The UR laser concept is best understood by comparing it to the conventional Fabry-Perot (FP) laser. The conventional semiconductor laser uses an FP cavity defined by two parallel facets. The lasing mode undergoes multiple reflections at the cavity mirrors and the mode is directly counter-propagated. In contrast, the UR laser is characterized by counter- propagating diverging cylindrical waves diverging from fixed virtual source points. By avoiding direct counter-propagation UR's suppress filamentation and maintain excellent beam quality with all the radiation diverging from fixed high-brightness virtual source points. Consequently, the UR laser is a true high brightness source since near diffraction-limited beam quality can be preserved even with broad laser cavities and under conditions of high current injection or optical pumping.

Lasers were epitaxially grown in our laboratory using a commercial solid-source molecular beam epitaxy system, configured specifically for antimonide alloy deposition. Heterostructures were deposited on 2 in. diameter (001) oriented GaSb:Te substrates. The laser design incorporates 14 type-II quantum wells that are placed 1000 Å apart in a 1.5 μm thick InGaAsSb waveguide. Two factors serve to reduce filament formation or antiguiding in these antimonide based "W" lasers. First, the lattice-matched GaSb clad layers provide only a small difference in the index of refraction relative to the waveguide ($\Delta n \approx 0.03$) such that the optical mode has very weak transverse confinement. These low confinement factor or "dilute" waveguides tend to suppress filament formation and allow for high brightness operation. Specifically, as the confinement factor, Γ, is lowered the filament gain decreases far more rapidly ($\approx \Gamma^2$) than does the modal gain which decreases in a linear manner [7]. A typical confinement factor for a telecommunications based GaAs laser would be $\Gamma \approx 0.020$ whereas we employ significantly smaller gammas, $\Gamma \approx$ 0.003-0.004. The second feature leading to a reduced tendency to form optical filaments are the intrinsically low antiguiding factors found in the optically pumped semiconductor (OPSL) heteroepitaxy. Indeed, Hakki-Paoli measurements of the antiguiding factor, α, for these quantum well lasers have yielded consistently low alpha values with $\alpha \leq 1$ [8].

Consequently, the implementation of a dilute waveguide structure, coupled with a low antiguiding factor epitaxy suggests that the application of a lateral mode control element, such as that embodied by an unstable resonator, may be highly effective for this class of W laser. Moreover, such a design may yield broad area mid-IR semiconductor lasers capable of both high power output and excellent lateral beam quality with operation near the diffraction limit.

The optically-pumped UR's are realized by mechanically polishing a diverging cylindrical mirror on one facet of a Fabry-Perot laser cavity. The chip is affixed onto a platform where it is mechanically polished using a rotating circular pad. This results in a high-quality cylinder with the desired radius of curvature and minimal facet damage. To assess mirror quality a Zygo Newview 6k optical profilometer was employed. Detailed scans of the polished mirrors show that high quality cylindrical figures are formed with a radius of curvature near 10.0 mm. Further, the scans reveal relatively minor surface abrasion; the scratches and digs are on the order of 38 nm or $\approx 1/30^{th}$ wave. The relative high quality of the curved facet reduces scattering and helps preserve the output power characteristics of the device. The output power for an OPSL UR emitting near 4.6 μm and operating near 84 K is shown in figure 1; the maximum output power for the UR is 6.63 W slightly less than a comparable Fabry-Perot laser which delivered 7.62 W of peak power for a 32 μs pulse (1 % duty cycle) This modest 14 % drop in power is largely attributable to the extra loss of the cavity due to geometric magnification of the radiation. This resonator magnification, M, is conveniently quantified as:

$$M = \frac{V+L}{V-L} = \frac{\sqrt{L^2+RL}+L}{\sqrt{L^2+RL}-L}$$

where L is the cavity length and R is the cylindrical mirrors radius of curvature. For a typical polished device with R = 10 mm and L = 3.5 mm the magnification factor is 3.1; for reference the FP cavity has a M = 1.

The regenerative reimaging of the circulating radiation is the critical mechanism leading to high brightness from the virtual source point. These virtual source points, shown as V_+ and V_- in figure 2, are located at a distance $V = \pm \sqrt{(L^2 + LR)}$ from the flat facet. The left virtual source, V_+, is at an object distance (V+L) from the diverging mirror with focal length

(-R/2). Upon reflection from the curved facet, the radiation forms a virtual image, V_{-}, at a distance (V-L) to the right of the curved facet.

In actual operation, the radiation is outcoupled from the flat facet, so that the virtual waist of the lateral mode is located behind the output facet at a refractively reduced distance, $D = V/n$, in which the index of refraction is given by $n = 3.82$. For a typical device geometry this reduced distance is inside the device at approximately 1.810 mm from the flat facet. The size of the diffraction limited waist, or spot diameter, is given by: $S_D = 2 \times \lambda \times F/\#$, where $F/\#$ is the resonator f-number and is simply the ratio of the distance back to the virtual source, D, to the pump stripe width, w ie.- $F/\# = D/w$. In addition to the high brightness generated by the regenerative reimaging of the virtual source points, the natural divergence of the propagating mode tends to mitigate self-focusing or filamentation, leading to further brightness improvements [7].

Figure 3 shows a comparison of best-focus points for a Fabry-Perot device and for a mid-IR unstable resonator device, both devices operating near 4.6 μm and pumped at 25 times above threshold. . Figure 3a shows the best-focus reimage results for the FP cavity operating at ≈ 30 × threshold; a degraded best-focus is evident. In comparison, a very clean virtual source spot with a full-width diameter of 70 μm is apparent in the UR image of Figure 3b. For the UR device, the far-field is realized by reimaging the virtual source points located a distance D from the flat facet. The measured diameter is close to the calculated diffraction limited spot diameter of $S_D = 67$ um. In addition, the virtual waist was located at a distance, D = 1.835 mm, back from the flat facet, very close to the value predicted from geometrical theory, ie.- $D = V/n = 1.810$ mm.

Longer wavelength UR's have also been fabricated and characterized. For a 9.13 μm emitting UR, at the maximum pump power of 43 W, the 3.5 mm long device delivered nearly 2.5 W of peak power. The virtual source was measured at 1745 μm back from the flat facet with an approximate diameter of 120 μm; consequently, the resonator is operating near the diffraction limit at ≈ 42 × threshold.

In summary, higher brightness operation is obtained from antimonide based W lasers by forming an unstable resonator cavity. The UR is realized by mechanical polishing a cylindrical mirror on one of the facets. Inspection of the mirrors using a Zygo profilometer reveals the formation of a high quality cylindrical mirror with a radius of curvature of ≈ 10 mm. The 3.5 mm long UR's set up a virtual source points near 1810 μm back from the flat facet in good agreement with theory. Both 4.6 μm and 9.13 μm resonators were demonstrated to operate near the diffraction limit at 25 × and 42 × threshold, respectively. The small optical confinement and small linewidth enhancement factors of these lasers undoubtedly contribute to the ability of the UR to maintain the lateral beam-quality. However, it is likely that the UR approach would be suitable for a wider range of semiconductor lasers including mid-IR, electrically injected quantum cascade lasers.

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Figure Captions

Figure 1. Peak power-power curves for L = 3.5 mm long Fabry-Perot and Unstable Resonator lasers operating near 4.6 μm and 84 K. To minimize thermal load on the laser the curves were collected under pulsed conditions: 32 μs pulse, 1 % duty cycle.

Figure 2. Schematic of unstable resonator showing virtual source points V_+ and V_-. L is the resonator length (3.5 mm), R is the radius of curvature of the polished cylinder ≈ 10 mm, w is the stripe width (FWHM = 250 μm) and D is the refractively reduced distance to the virtual source, D = 1810 μm.

Figure 3a. Re-image of degraded best-focus at 30 × threshold for the Fabry-Perot laser.

Figure 3b. Re-image of virtual source at 25 × threshold for the 4.6 μm UR. The virtual source size indicates the lateral mode is nearly diffraction limited

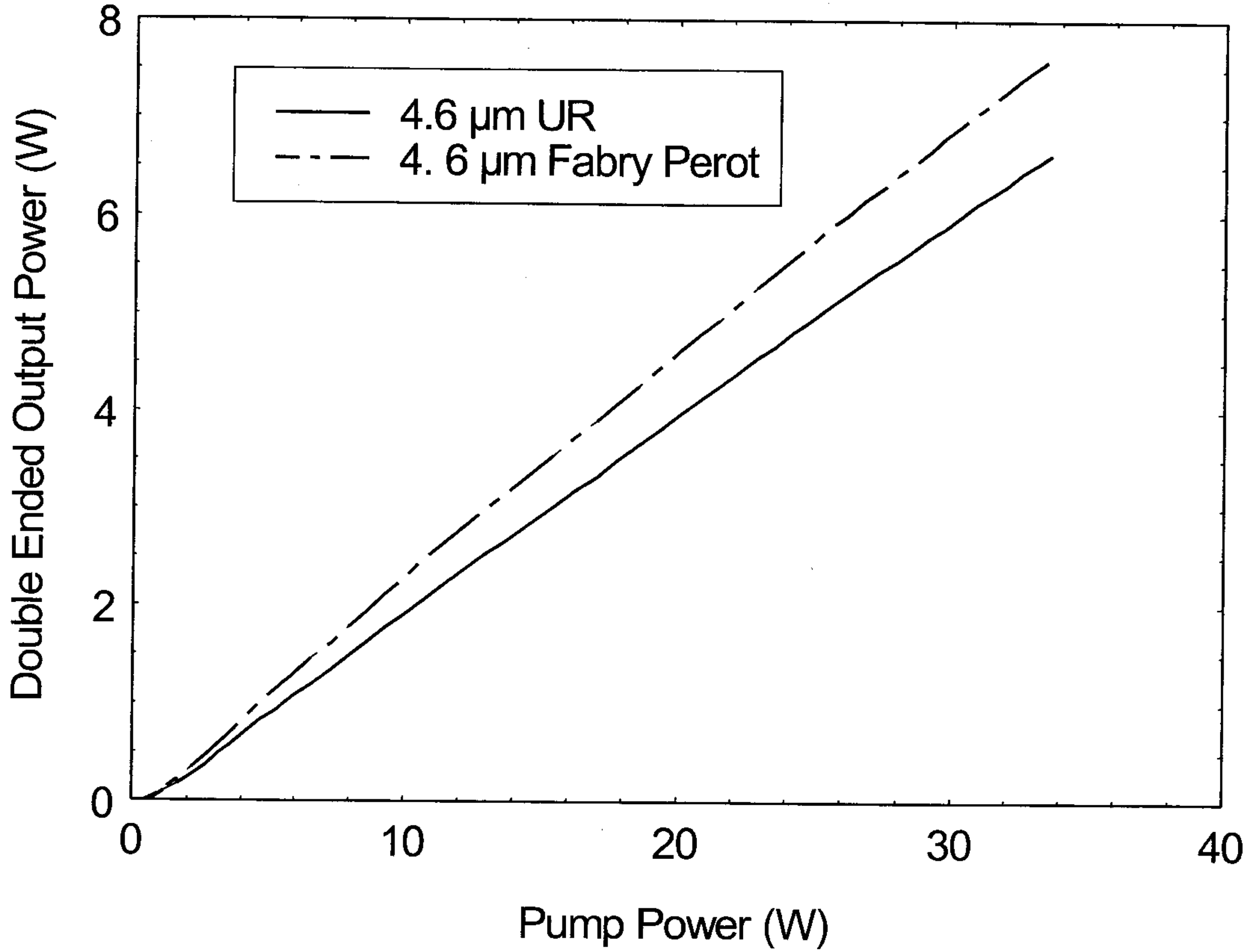
8
6
4
2
0
0
10
20
30
40
4.6 µm UR
4. 6 µm Fabry Perot
Double Ended Output Power (W)
Pump Power (W)

Figure 1.

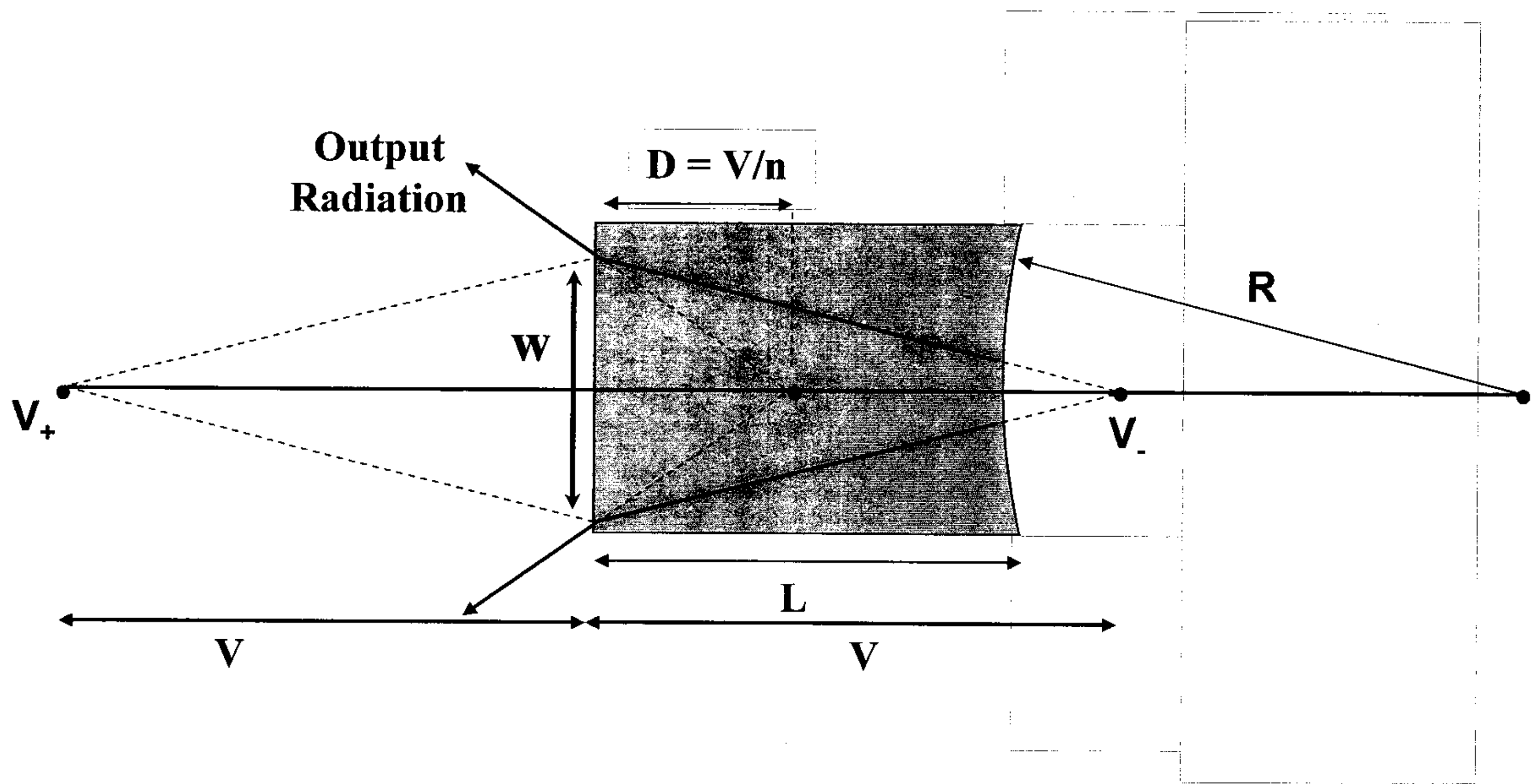

Figure 2.

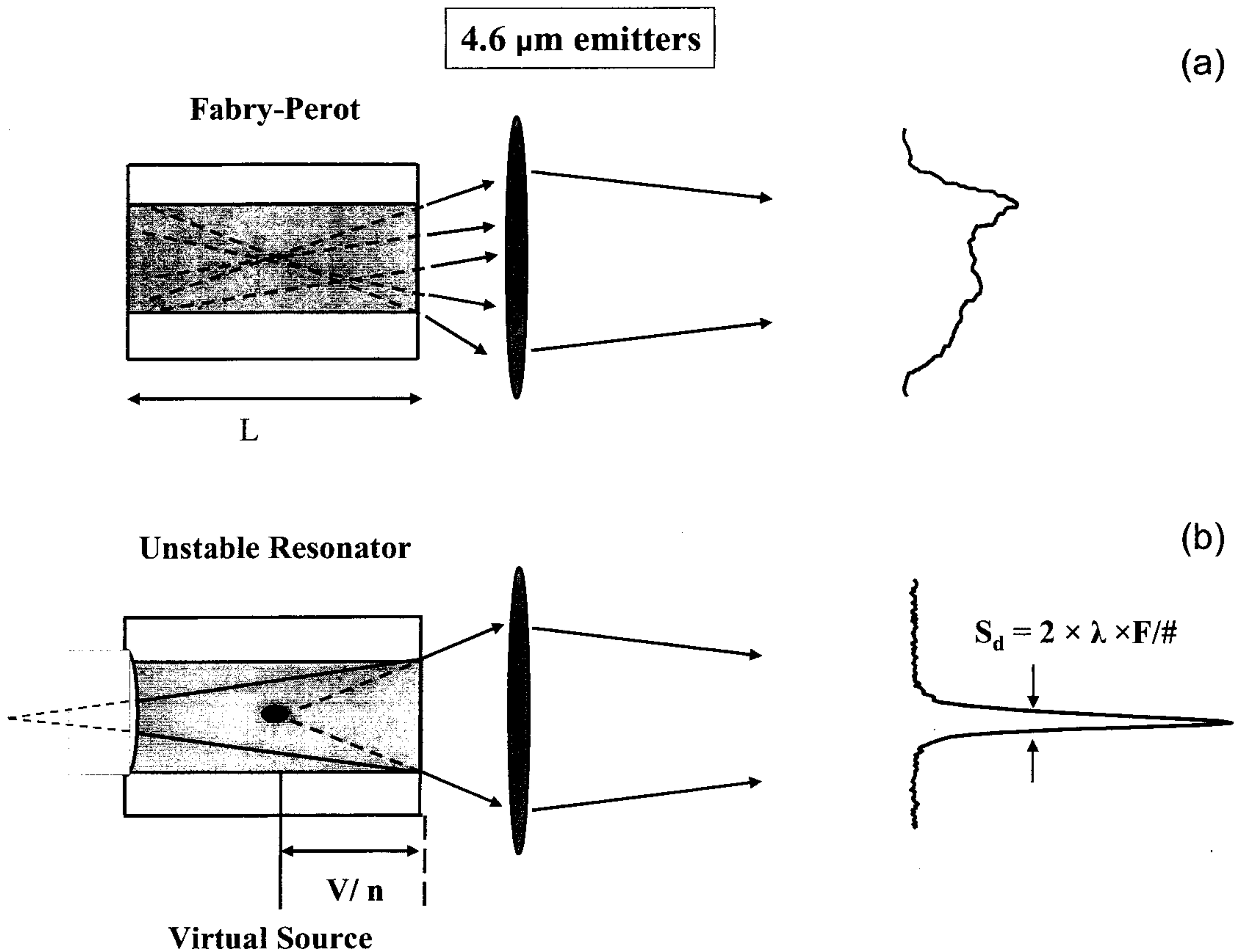
4.6 μm emitters
(a)
Fabry-Perot
L
(b)
Unstable Resonator
$S_d = 2 \times \lambda \times F/\#$
V/ n
Virtual Source

Figure 3.